Induced micro-seismicity and mechanical response during the experimental flooding of an iron ore mine

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INDUCED MICRO-SEISMICITY AND MECHANICAL RESPONSE DURING THE EXPERIMENTAL FLOODING OF AN IRON ORE MINE.

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ABSTRACT: *In order to understand the impact of flooding on mining collapses and its relationship with the micro-seismic activity, a controlled experiment of cavity flooding was performed in an underground iron mine. 134 micro-seismic events (magnitude < 0) were recorded during the experimental flooding. The micro-seismic activity showed a correlation with the water injection evolution in the cavity suggesting that micro-seismic activity was triggered by the stress modification induced by water introduced in the cavity. Two main processes are suggested: a) micro-seismic events (class 1) forming a group of perfect multiplet families and a frequency spectrum higher than 200 Hz; these events were triggered by the reactivation of pre-existing fractures; b) micro-seismic events (class 2) not forming a group of multiplets families with a frequency spectrum lower than 200 Hz; these events would be the result of complex interactions between the increase in elastic stress and the cumulative effects of increased pore pressure. The largest seismic events were triggered only during the water rise in the cavity suggesting that the water rise phase is a particularly sensitive trigger for the largest mechanical instabilities.*

KEYWORDS: *micro-seismicity, flooding, minning, collapses, water level*

RÉSUMÉ: *Une expérimentation d'ennoyage contrôlé a été mise en œuvre dans une mine de fer souterraine afin d'étudier l'impact de l'ennoyage sur les instabilités minières et les corrélations avec l'activité micro-sismique. 134 évènements micro-sismiques (magnitude < 0) ont été enregistrés lors de l'ennoyage du site expérimental. L'analyse de l'activité micro-sismique montre une corrélation significative avec l'évolution du niveau d'eau dans la cavité et suggère que cette activité a été induite par les changements de contrainte générés par l'ennoyage de la cavité. Deux processus principaux sont proposés : a) évènements micro-sismiques (classe 1) regroupés en famille de multiplet avec des fréquences supérieures à 200 Hz; ces événements ont été induits par la réactivation des fractures préexistantes; b) événements micro-sismiques (classe 2) qui ne sont pas regroupés en famille de multiplet avec des fréquences inférieures à 200 Hz; ces événements semblent être déclenchés par les interactions complexes entre l'augmentation des contraintes élastiques et l'effet cumulé de l'augmentation de la pression des pores. Les événements micro-sismiques les plus importants ont été induits uniquement pendant la montée de l'eau dans la cavité suggérant que cette phase transitoire de montée de l'eau serait la plus sensible aux instabilités mécaniques.*

MOTS-CLEFS: *micro-sismicité, ennoyage, exploitation minière, effondrement, niveau d'eau*

1. Introduction

A triggered seismicity occurs when the change in the stress state by an external factor is sufficient to cause failure. This can occur either due to an increase in the stress induced by field driving the fault or due to a decrease of the shear strength of the fault. Fletcher and Sykes (1977) show that an increase in pore pressure of 1 to 5 MPa may be enough to trigger seismic events of magnitude –1 to 1. Simpson and Negamatullaev (1981) found that a change in water level only a few meters (of the order of 0.01 MPa) is enough to trigger seismicity. The seismic activity in this particular case is associated with the filling of a number of large water reservoirs. Two different stress modifications have been suggested as the dominant mechanisms responsible for seismic activity during the filling of large reservoirs: 1) the direct effect of loading, through increased elastic shear stress; 2) the effect of increased pore pressure, through decreased effective normal stress (Simpson 1988).

During the mining activities in the underground iron mines in Lorraine (East of France) over a period of 100 years, the ground water table was lowered due to the mine drainage. At the end of the mining, the drainage pumps were stopped and the excavation began to be flooded. Some mining collapses occurred during this transient stage of flooding. In order to understand the possible impact of flooding on mine collapses, several experiments were performed in the framework of GISOS (Research Group on the Impact and Safety of Underground Workings) research program. An experimental site was selected in the iron mines of the Lorraine basin (Tressange mine) and a controlled experiment was carried out between March 2002 and July 2003 for simulating the flooding of an abandoned mine. The Tressange site was isolated with watertight barriers and the cavity was filled with water for a period of 17 months. The aim was to study the impact of flooding on the mechanisms involved in mine instabilities and the relationship with micro-seismic activity. This paper presents the controlled field experiment simulating a mining cavity flooding, the micro-seismic activity triggered during the cavity flooding and its correlation with the water level and the associated mechanical instabilities.

2. Geological setting and description of experimental site

The experimental site is located in the Tressange mine which belongs to the iron ore basin of France. This iron basin is almost 100 km long and 40 km wide, from Luxembourg to Nancy (France). The iron ore formation has 60 m thickness and in the deepest iron ore layers is 250 m deep. The mining method was room and pillar under Tressange town. In this area three iron-bearing layers were mined: the brown-iron layer (the deepest layer at about 225 m), the grey-iron layer, and the yellow-iron layer. These three mined iron layers are separated by inter-seam rocks (clay, limestone) and by superimposed pillars of 18 m width and 28 m length. The flooded level of the field experiment was in the brown-iron layer where galleries with around two pillars (G and F) were entirely flooded. The areas around ten other pillars were partially flooded (figure 1a). The cavity was isolated with ten tight concrete barriers built in the galleries and delimiting the flooded area.

3. The local micro-seismic network

A micro-seismic network composed of three 3D stations was installed in the inter-seam rocks between the flooded brown-iron and grey-iron layers. Each seismic station contains geophones with a frequency-band between 40 Hz and 1.5 kHz cemented at a depth of 5 m in vertical boreholes drilled from the galleries at the bottom of the grey layer (figure 1b). The geometry of the seismic network allowed monitoring of the flooded pillars and the inter-seam rocks. Date acquisition was carried out using a computer at a sampling rate of 10 kHz and a resolution of 16 bits. The sensors were connected to the acquisition system and the complete network was tested using hammer blows.

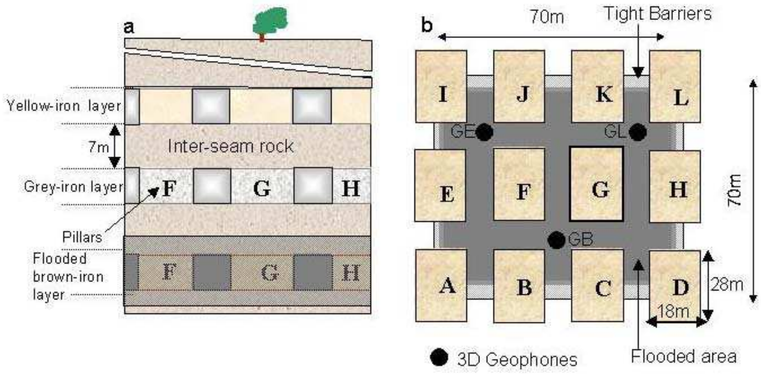

Figure 1 : Experimental site: a) Vertical section of three iron layers mined: yellow-iron layer, grey-iron layer and the flooded brown-iron layer. b) Local micro-seismic network installed in the inter seam rocks between the flooded brown-iron layer and the grey-iron layer (sensors GB, GE, GL)

4. Micro-Seismic activity and analysis

During the flooding period, three types of micro-seismic activity were recorded:

- seismic events associated with mine blasting (open air quarries). The local seismic network recorded systematically all blasting related to the mining operations located at a distance of 6 km from the experimental site. These mine blasting signals are of low frequencies at about 30 Hz (figure 2a)
- seismic events associated with two large natural earthquakes which located at about 100 km from the experimental site: the earthquake (Richter magnitude 4.7) recorded in the region of "Aachen" 22nd July 2002, local time 07:45; the second earthquake (Richter magnitude 5.4) recorded at the region of "Saint Dié" 22nd February 2003, local time 21:41 (figure 2b). The signals were recorded during 32 seconds with low frequencies of about 10 Hz.
- seismic events triggered during the flooding site. 134 micro-seismic events were recorded from which the seismic signature is completely different from those associated with blasting or earthquakes. Indeed, these events are of short period (a few hundredth seconds) with a large frequency band, between 50 Hz and 1.5 kHz that corresponds the highest frequency of the geophones (figure 2c). In the following, the analysis of these 134 micro-seismic events recorded during the experiment of cavity flooding is presented.

a.
b.
c.

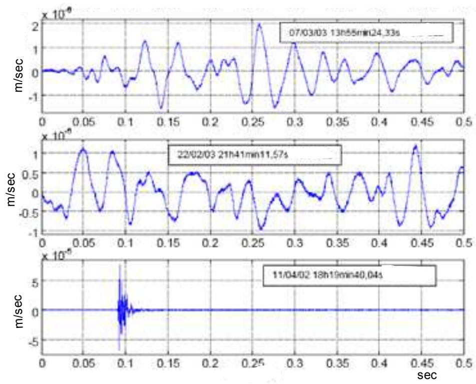

Figure 2: Example of seismic events recorded during the cavity flooding : a) seismic event associated with mining blasting; b) seismic event associated with natural earthquake; c) local seismic event induced by the cavity flooding. The example shows signals recorded by the vertical sensor GL.

4.1. Micro-seismic activity and water level

The correlation between 134 micro-seismic events recorded during the experimental flooding and the water level could be divided in to mainly four phases (figure 3):

- Phase 1: before flooding (~15 days of monitoring). Only one seismic event was recorded.
- Phase 2: during flooding (~15 months). 45 micro-seismic events were recorded with three particular periods: p*eriod 1* : after beginning of the water injection, the micro-seismic activity started when the water level in the cavity reached 2.5 m high (the cavity height is 4.5 m), the micro-seismic activity increases continuously with flooding. *Period 2* : the cavity is flooded but the water level is not yet completely stable and the water level is still raising progressively before completely stabilising; in this period, the micro-seismic activity is lower than in period 1. *Period 3*: the cavity is completely flooded, the water level is constant and kept at its maximum level for about 10 months, the micro-seismic activity continues to increase (see figure 3).
- Phase 3: during drainage (~40 days). The micro-seismic activity is characterised by a strong increase and 88 micro-seismic events were recorded.
- Phase 4: When the cavity is completely drained (~30 days of monitoring). No micro-seismic event was recorded during this period.

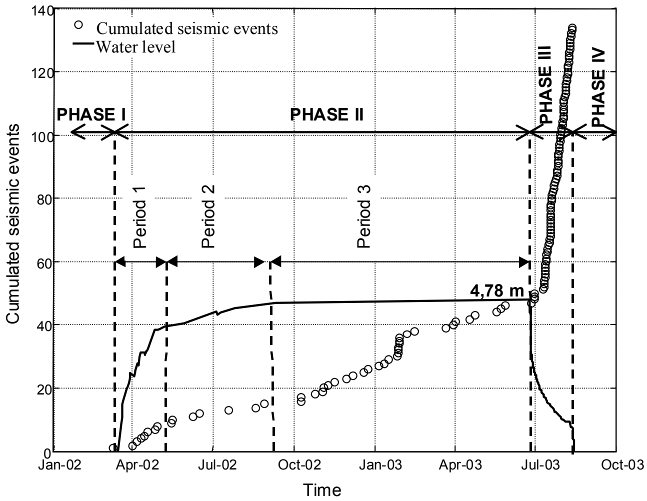

Figure 3: Correlation between micro-seismic events recorded during the experimental flooding and the water level. The experiment could be divided in to mainly four phases: I. before flooding; II. during flooding; III. during drainage; IV. the cavity was completely empty.

The small number of seismic stations and the unfortunate malfunctioning of the horizontal sensors make it impossible to locate the seismic events. Thus, we propose a spatial classification based on the signals only recorded by the vertical sensors for which the arrival times are also taken into account. Two classes of seismic events were identified :

- Class 1: seismic events recorded only by one station. 107 events recorded only by the station GL and 2 events recorded only by the station GB.
- Class 2: 25 seismic events recorded by all the sensors (GL, GB, GE).

The signal characteristics of these two classes are also completely different. Approximately 95% of the events recorded only by one sensor (class 1) show a frequency spectrum higher than 200 Hz and around 99% of the events recorded by all stations (class 2) are associated with a frequency spectrum lower than 200 Hz (see figure 4).

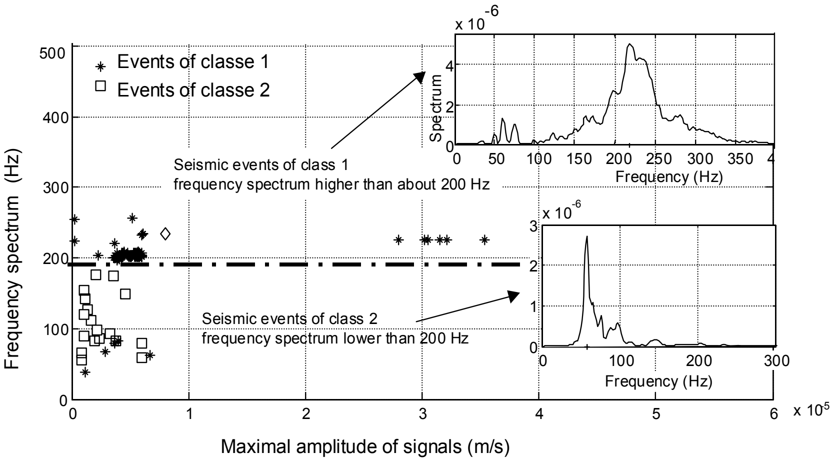

Figure 4: Classification of seismic events in class 1 and class 2 following the frequency spectrum

The signature was evaluated using the doublet technique or multiplet selection applied to all the seismic events. The aim was to identify seismic event families based on the assumption that each family belongs to the same failure mechanism. We define multiplets as a set, and a doublet as a pair with a similar appearance. The objective is to characterize the degree of similarity of a pair of events using the modulus of the coherency spectrum, which is the smoothed cross-spectrum normalized by the smoothed autospectra of each windowed seismogram (Got 1994). The smoothing function of the spectral densities is given by Fourier Transform. The multiplet selection showed that the events of class 1 (signals recorded only by the station GL) clearly form a group of two multiplet families: family 1 belongs to the seismic events recorded only during the cavity flooding (Figure 5a) and family 2 belongs to 86 events recorded during the cavity draining which 81 events form a group of perfect multiplet (figure 5b). Micro-seismic events of class 2 do not form a group in a multiplet family.

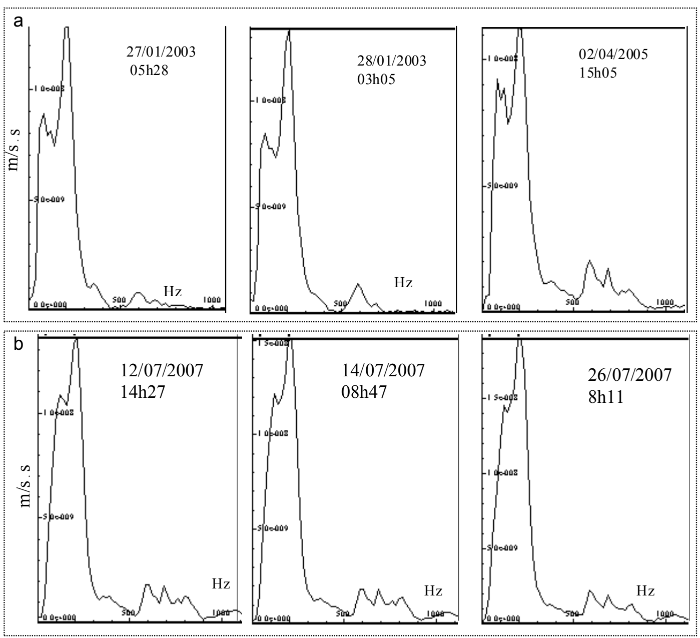

Figure 5: Examples of signals regrouped as a multiplet belong to micro-seismic events of class 1

4.2. Seismic energy released and mechanical measurements

The estimation of seismic energy released by each seismic event was determined using the following equation:

$$E_z = \sum_{i}^{N} V_i^2 \Delta t \qquad (1)$$

Where E_z is the estimated seismic energy recorded by each vertical sensor, V_i is the amplitude in m/s for each pulse duration (Δt) and N the total point numbers. The calculation was performed for each vertical geophone recording a signal. The energy of the seismic events was set as the average energy calculated for each sensor. For the evaluation of the size of seismic events recorded during the experimental flooding, we propose an approximate comparison with the events induced by underground mining; the magnitude is calculated using a classical and empirical correlation between seismic energy and local magnitude (Gibowics 1963):

$$M_L = a \log (E) + b \qquad (2)$$

where E is the energy; a and b are the coefficients fitting the local magnitude (M_L) determined from the national or international seismic network. Figure 6 shows the correlation between seismic energy and magnitude proposed by several authors for evaluating the local magnitude of mining induced seismicity (Senfaute 1995, Tobyas and Mittag 1992, Gibowics 1963). The extrapolation of these correlations towards smaller events suggests that the magnitude range of seismic events recorded during the cavity flooding would be in the range of –2 to –3 (figure 6). This range could be compared with the magnitude (about –2.5) of micro-seismic events induced by flooding that occurred at the underground Ikuno mine in Japan (Ogasawara et al 2002).

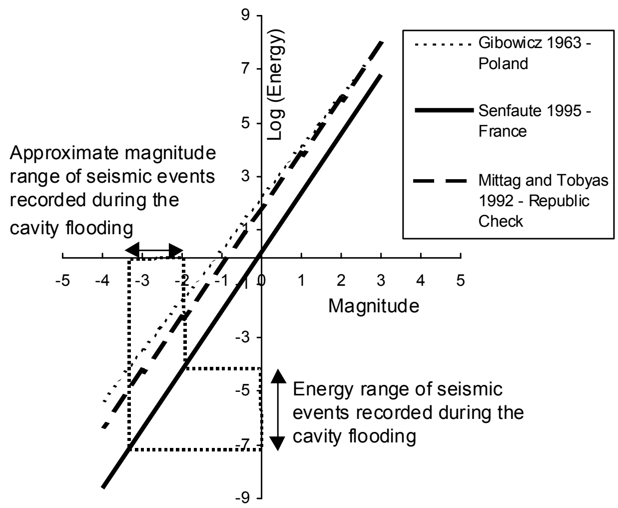

Figure 6 : Correlation between seismic energy and magnitude used by several authors for evaluating the local magnitude of mining induced seismicity and extrapolation towards smaller events recorded during the cavity flooding.

In addition to the geophysical monitoring, mechanical behavior of the cavity was by measuring the gallery convergence during the cavity flooding. Displacement sensors (LVDT type with precision of 0.02 mm) were installed between the floor and the roof of the cavity for measuring the evolution of the vertical displacements. Figure 7 shows the seismic energy released by each seismic events, the correlation between the cumulated seismic energy of each class of events, the displacements of the gallery wall and the water level measured using electromagnetic sensors. The evolution of seismic energy released during the cavity flooding shows that the largest seismic events were recorded during the period when the water level was increasing in the cavity. The largest vertical displacements of the gallery convergence were also recorded during the same period. When the cavity was completely filled and the water level remained constant the released seismic energy was smaller than that of the last period. During drainage of the cavity, a significant number of seismic events of class 1 (recorded only by sensor GL) were recorded with a seismic energy similar to that of the events triggered during the period of constant water level.

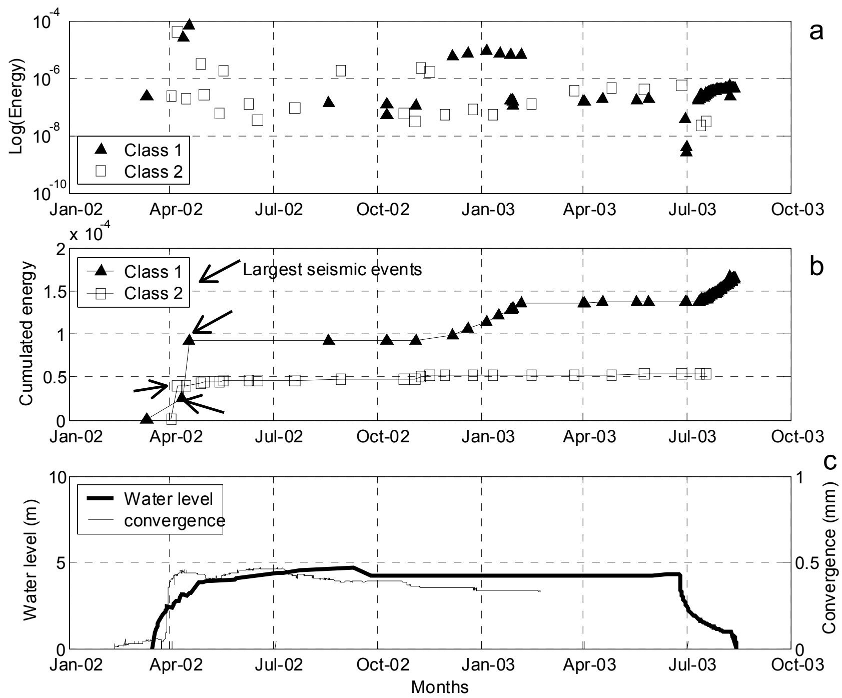

Figure 7 : a) Seismic energy released by each seismic event; b) Cumulated seismic energy of class 1 and class 2 events c) the evolution of the water level into the cavity and the vertical displacements of the gallery .

5. Discussion

A significant but small seismic activity (magnitude < 0) was recorded while a controlled flooding experiment was performed in an underground iron ore mine cavity. The seismic activity increased progressively with the water level in the cavity and shows a clear correlation between water level and the triggered seismic activity. The seismic activity would be triggered by the stress change induced by water. Two processes might be responsible for the micro-seismicity triggered during the flooding:

- Seismic events of class 1 recorded only by one sensor (sensor GL). This seismic activity is interpreted to be associated with the reactivation of pre-existing cracks in the roof. Field observations have confirmed that the sensor GL was effectively located in an area with significant natural fractures. This class of events has been regrouped in perfect multiplet families: the family 1 which the events were recorded during the cavity flooding and the family 2 which events were recorded during the drainage phase. However these two multiplet families have also strong similarities with a relatively mono-spectral frequency spectrum and a main frequency peak at 200 Hz (see figure 5). The multiplet families indicate that this class of events belongs to the same failure mechanism and suggests that the reactivation of pre-existing fractures triggers the seismic events of class 1. These seismic events were most likely triggered by the fractures reactivated during the water injection in the cavity and during the rapid decrease of the water level. However the seismic activity disappeared when the cavity became completely empty. These results show that seismic events are induced by an elastic response to the cavity loading mainly affecting the sectors with pre-existing fractures. Simpson et al (1988) and Bell and Nur (1978) concluded from the investigations concerning induced seismicity related to reservoirs that the dominant mechanism responsible for the triggered seismicity is the direct effect of loading through an increased elastic shear stress.

- The interpretation of the failure mechanism is more complex for seismic events of class 2. This population does not form a group of doublets or multiplets suggesting that they have not been associated with any particular pre-existing fracture. These seismic events were mainly triggered during the cavity flooding. No event was recorded prior to the site flooding and only one event was triggered during the cavity emptying. Following the research of Bell and Null (1978), Simpson (1986) on induced seismicity related to reservoirs, we can suggest that these events result from complex interactions between the elastic stress increase, the cumulative effects of an increased pore pressure, diffusion mechanisms and the initial stress state. An explanation of failure mechanisms is proposed by Grgic et al 2006 who applied numerical modelling to the experimental site and concluded that the liquid pressure at the walls, floors and roofs, generate transient tensile mean effective stresses at the roof and floor. Tensile stresses, localized on the cavity (roofs and walls) induced tensile failures which would be responsible for triggering micro-seismic activity.

The largest seismic events were triggered during the water rise in the cavity. These events were triggered before the water level reached the roof of the cavity and remained constant (figure 7b). These results suggest that the water rise phase is a particularly sensitive trigger for the largest seismic events. Displacement sensors used to measure the gallery roof-floor closure showed that the displacement increases only during the water rise in the cavity. These results confirm that the first water filling phase, before the water level reaches a steady-state phase, is the most sensitive that may result in mechanical instability of the cavity. Similar results have been observed by Simpson et al (1998) who studied two reservoirs sites: Monticello in USA and Manic 3 at Quebec. At both sites, the seismicity reached a peak near the time of first stage filling, and gradually decayed as the water level remained constant. The largest seismic events occurred before the water level had reached its maximum level.

6. Conclusions

A local seismic network installed in an abandoned iron ore mine cavity recorded significant seismic activity during a flooding experiment. The results show clear correlation between the water level and the seismic triggered activity suggesting that seismic activity has been triggered by the stress modification induced by the water filling the cavity. Two kinds of seismic activity have been recorded: a) seismic events regrouped in multiplet families which were triggered by an elastic response to the cavity loading affecting directly the sectors with pre-existing fractures; b) seismic events which are not regrouped in multiplets and probably result from complex interactions between an elastic stress increase, the cumulative effects of increased pore pressure and the initial stress field.

The largest seismic events were triggered during the water rise in the cavity and before the water level reached the roof of the cavity. When the cavity was completely filled, the water level was kept constant, and during the draining phase, the energy of seismic events was smaller than that of the events triggered during the water rise. These results suggest that the water rise phase corresponds to a sensitive stage regarding the mechanical stability of mines and cavities subjected to flooding.

7. Acknowledgements

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